Navigating MarCO, the First Interplanetary CubeSats

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Abstract

The NASA's Mars Cube One (MarCO) probes are twin 6U CubeSats that were launched into space on May 5, 2018. The MarCOs shared a launch vehicle with NASA's InSight mission, separating from the Atlas V Centaur upper stage after InSight. The MarCOs were injected into an Earth-Mars transfer trajectory and were independently navigated to the proximity of Mars. On 26 November, 2018 the MarCO probes flew by Mars as the InSight lander descended to the surface, providing real-time relay of InSight UHF data back to the Earth. This paper describes the approaches used to design the MarCOs' trajectories and to navigate them to Mars, presenting the challenges of navigating and operating CubeSats in deep space, and the technological firsts achieved by the MarCO mission.

Keywords: CubeSat, navigation, MarCO, interplanetary.

Introduction

A CubeSat is a common type of miniaturized spacecraft that is sized as a multiple of approximately 10 cm sided cube units. Hundreds of CubeSats have been launched into Earth's orbit for technology demonstrations, science research, and student training. CubeSats are usually deployed using standardized dispensers. Using the CubeSat standard [1] can reduce the construction, integration, and launch cost of small spacecraft. The Mars Cube One (MarCO) probes were built in conformance with the 6U CubeSat standard, and are the first CubeSats to escape Earth's orbit and fly into deep space. MarCO features innovative technologies for CubeSat attitude determination and control, propulsion, power generation, and communications. Packing all the subsystems required for interplanetary flight operations into a 13.7 kg spacecraft presented challenges especially in the areas of energy management and communications, as the size of the solar arrays and antennas needed to be sufficient to sustain the necessary signal levels. The MarCOs were launched into space on May 5, 2018, hitching a ride alongside InSight in its journey to Mars. The MarCOs flew independently of InSight and passed the proximity of Mars on November 26, 2018, while relaying the InSight's Entry, Descent, and Landing (EDL) data back to Earth.

Mission Overview

The MarCO project is a technology demonstration mission with the goal to test a number of small spacecraft technologies in deep space. The mission took advantage of a very favorable launch performance for InSight [2] that allowed for small secondary payloads to be added to its launch vehicle. The MarCO probes were integrated into Tyvak NLAS Mark II dispensers that were attached to the aft bulkhead carrier of the Centaur upper stage of InSight's Atlas V 401 launch vehicle. The MarCO probes were released from their dispensers seconds after InSight separated, in opposite directions almost orthogonal to the InSight separation direction. They flew independently of each other and InSight for their journey to Mars. During cruise, they demonstrated to capability of small probes to operate in deep space, communicating with NASA's Deep Space Network (DSN) antennas on the ground, performing attitude and trajectory control, and managing their data, power, and thermal state. In preparation for their

Mars flyby, they were positioned to relay the UHF data that InSight transmitted while it descended to the surface of Mars. Both MarCOs performed the InSight relay successfully and also took pictures of Mars during the flyby. Currently they are in separate heliocentric orbits shuttling between the orbits of Mars and the Earth.

Probe Configuration

Each MarCO probe had a mass of about 13.7 kg at launch and dimensions while stowed of 36.6 cm by 24.3 cm by 11.8 cm, about the size of a briefcase. After being released, solar panels unfolded, and the following days a high gain antenna, composed of a feed element and a reflectarray, and a UHF antenna for communication with Insight were also deployed.

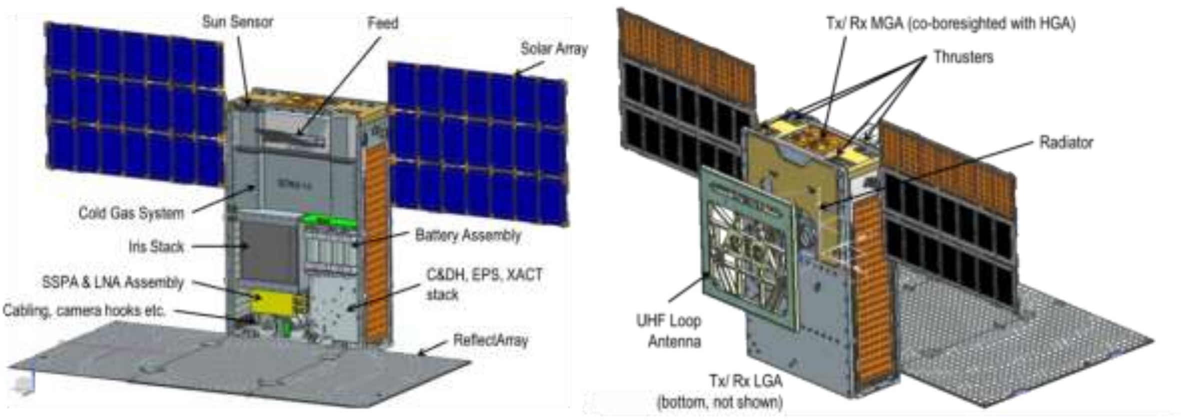

Fig. 1: Probe configuration in deployed state (without thermal blankets)

Tracking and communications system

Each MarCO probe is equipped with an Iris radio [3] capable of receiving and transmitting in deep space X-band and also of receiving in the UHF band. This radio can coherently transpond X-band Doppler and ranging using the standard deep-space protocols and ratios, and can also produce tones suitable for performing delta-differenced one-way range (ΔDOR) [4]. Each probe carries a set of low gain antennas with one single-element patch for receive and another for transmit, a set of medium gain antennas with two patches for receive and two for transmit, and a transmit-only high gain antenna with an eight-patch feed element and a reflectarray. The reflectarray [5] allows for an 8 kbps rate at a 1 AU distance, while being able to fold into a space less than 1.4 cm tall. In addition, the probes carry a deployable loop UHF antenna to receive the data transmitted by InSight.

Attitude control and propulsion system

The MarCO probes are three-axes stabilized, each carrying Blue Canyon Technology's XACT attitude determination and control system equipped with a star tracker, two sets of sun sensors, and a three-axis reaction wheel assembly [6]. When the probes are not communicating with the DSN, they are set to slowly rotate with their solar panels pointed to the Sun in order to charge the batteries and reduce the average solar torque in body-fixed axes. Each probe carries a VaCCO propulsion system with a propellant tank, a plenum, and eight 25 mN class thrusters, four for attitude control and four for trajectory control. The system is capable of 755 N-sec of thrust, has a specific impulse of around 40 seconds, and uses R236fa—a non-toxic inert fluid commonly used in fire extinguishers—as propellant [7]. The use of the propulsion system was constrained by the power and energy available to the spacecraft, and trajectory correction maneuvers were planned to be broken up in segments of not more than ten minutes in duration to ensure that the battery charge would stay within safe margins.

Key Navigation Requirements

The high-level requirements on the MarCO project were to launch with InSight and to perform 8 kbps real-time bent-pipe relay of InSight's UHF data during EDL, while ensuring no harm to the InSight mission and complying with launch and planetary protection requirements. In order to launch with InSight and perform the relay function during EDL, the project needed to determine and correct the trajectory of the probes to guide them into trajectories that would ensure an adequate range to InSight during EDL. The distance between the MarCO probes and InSight were monitored to ensure that the MarCOs would not contaminate InSight and that their trajectories would not intersect. For planetary protection, xtensive Monte Carlo analyses were performed to assess the probability of the probes impacting Mars over the next 50 years after launch, and this data was combined with vehicle break up and burn up analysis in order to ensure compliance with NASA planetary protection requirements. The relay trajectory design took into consideration the planned trajectory and attitude of both the MarCO probes and the InSight spacecraft, as well as the UHF antenna patterns in both spacecraft, in order to ensure an adequate link budget during relay. Navigation was allocated propellant for 33 m/s of trajectory correction maneuvers, with the rest of the propellant allocated for attitude control and margin. Navigation had to devise ways to deal with a high uncertainty in maneuver execution errors, since the MarCO attitude control and propulsion systems had not been used before in deep space.

Navigation System

The MarCO navigation system was built using JPL's operational navigation software, the Mission analysis and Operation Navigation Toolkit Environment (MONTE) [8]. It included trajectory modelling and determination, relay target optimization, and maneuver design and analysis. The system was integrated using a user interface that allowed for a high level of automation. Navigation functions during cruise included the following:

1. Estimating the spacecraft trajectory based on radiometric tracking data: coherent 2-way Doppler and range, and ΔDOR measurements.
2. Generating spacecraft ephemerides and ancillary trajectory data products for the DSN and the mission operations team.
3. Performing relay trajectory analysis to assess and optimize the UHF link budget during relay.
4. Determining the desired ΔV vector for TCMs and verifying the maneuver implementation generated by the spacecraft team.
5. Providing real-time tracking data residual monitoring during TCMs, relay, and other dynamic events.
6. Reconstructing TCM ΔVs using pre- and post-TCM tracking data as well as propulsion and GNC telemetry.
7. Producing the optimal spacecraft attitude for initial operations, for TCMs, and for relay operations.
8. Using tracking and telemetry data to estimate the translational effect of the propellant leaks and the associated mitigation activities.

The reminder of this section describes the data, models, and processes used for navigation analysis.

Tracking Data

The tracking data types used for MarCO orbit determination were: two-way and three-way coherent Doppler, two-way coherent sequential range, and ΔDOR. The data was collected by the 34-m and 70-m antennas of the Deep Space Network at Canberra, Australia; Goldstone, California; and Madrid, Spain. Doppler data provided a high resolution, high accuracy measurement of the line of sight velocity of the spacecraft with respect to the ground antennas, at a level of about 0.1 mm/s for 60-second compression time. A particularity of the MarCO software-defined IRIS radio is that it introduces a constant, small Doppler bias into the measurement that had to be estimated during the trajectory determination process. Range provided an accurate measurement of the line-of-sight distance to the spacecraft, with an accuracy of a few meters. Spacecraft range delays were measured during the pre-launch testing and were used and also estimated in the orbit determination process. ΔDOR provided a measurement of the plane-of-sky angle error with respect to nearby quasars, with accuracies at the 60 ps level, or around 300 m at the Mars arrival distance during final approach. Doppler and range were collected during the dedicated MarCO tracking passes, usually with a duration of one to three hours, with range being performed only for a fraction of the pass duration. The ΔDOR measurements were performed at the same time as for InSight, but with at most one MarCO probe being tracked during each InSight session. The DSN also provided media, troposphere and ionosphere calibrations, and Earth orientation calibrations that were used when processing the tracking data. Table 1 lists the nominal tracking schedule for each of the MarCO probes. This schedule was sparse when compared with InSight, which had continuous tracking during its final approach and up to 14 ΔDOR sessions per week. Additional passes were scheduled during TCMs, and the schedule was changed to shift passes from one probe to the other when the operational activities required it.

Table 1: MarCO tracking schedule (per probe)

Start	End	Doppler/Range Passes	ΔDOR Sessions
Launch	Launch + 30 days	Daily	None
Launch + 30 days	Flyby – 28 days	3 per week	1 per week
Flyby – 28 days	Flyby – 14 days	5 per week	4 per week
Flyby – 14 days	Flyby	Daily	4 per week

Trajectory Modeling

The MarCO trajectories were modeled using the gravitational forces due to the Sun, Earth, Moon and planets, based on the DE430 JPL solar system ephemerides. Solar radiation pressure and thermal re-radiation were modeled using plates for the major probe components and assuming the nominal—battery charging—probe attitude. The probes actually flew at different attitudes, but the nominal attitude produced a good guess of predicted acceleration when the actual attitude could not be predicted or modeled accurately. Initially, the models used were the same for both probes, with a global scale factor for radiation pressure estimated as well as daily stochastic biases in the three directions, but after the leak developed for MarCO-B, this probe required a much more sophisticated model that is described in detail in [9], incorporating GNC and propulsion telemetry data to estimate and predict the acceleration generated by the thruster leak and the impulse produced by plenum blowdowns. Angular momentum reduction and trajectory correction maneuvers were modeled as impulse or finite burns and estimated in the navigation filter.

Orbit Determination

The orbit determination filter performed a weighted least-squares minimization of the tracking data residuals and the a-priori parameter constraints. A number of data arcs were used during operations, with the start of the data arc advanced in order to remove earlier data and reduce the amount of time required to generate an acceptable orbit determination solution. Alternate filter configurations were evaluated for every orbit determination solution to assess the effect and contribution of the different data types, to assess the effect of estimating Doppler and range biases, to test different constraint levels for estimated TCMs and other small forces, and to evaluate different future non-gravitational acceleration assumptions.

Trajectory Design

The post-launch trajectories for the MarCO probes were determined by the launch targets selected by the InSight project, by the injection errors, and by the way the probes were released. The MarCO project, as a secondary non-interfering payload, could not determine how the launch vehicle should be targeted. The MarCO team did study the predicted post-launch trajectories and verified that they were acceptable for MarCO, though an unacceptable verdict would have been a decision not to launch. Part of the analysis was to study the probability of impacting Mars over the next 50 years after launch and these data were used, together with a vehicle break up and burn up analysis, to prove that MarCO complied with planetary protection requirements. Pre-launch navigation analysis was also performed to determine flyby targets for every day of the InSight's launch period and to study how much propellant would be needed to achieve those targets with 99% reliability. The targets were calculated to optimize the UHF link budget during InSight's EDL. Using InSight planned trajectory and the InSight and MarCO UHF antenna patterns, the flyby altitude, inclination, and time were varied and a link margin profile for each trajectory was calculated. An optimal MarCO inertial attitude was selected for each trajectory, with the HGA boresight pointing to Earth and the UHF boresight pointed towards InSight. Fig. 2 shows an example for one possible trajectory. The result was a map like that in Fig. 3, showing on the encounter B-plane the Mars impact disk for the surface and the atmosphere, the InSight target, the contours of relay margin starting at 3dB, and the optimal points based on the nominal analysis and the optimal arrival time. As can be seen in Fig. 3, the MarCO targets were very wide, especially when compared with the 10 km InSight entry target. There were two acceptable regions due to the InSight antenna pattern, since it had a null at the top of its backshell [10]. The flyby distance was a balance between space loss at greater distances and wider excursions of InSight in the MarCO antenna pattern at shorter distances. Each probe was targeted to one of these regions to ensure that at least one probe would be able to relay the InSight data in the case of an unfavorable InSight attitude.

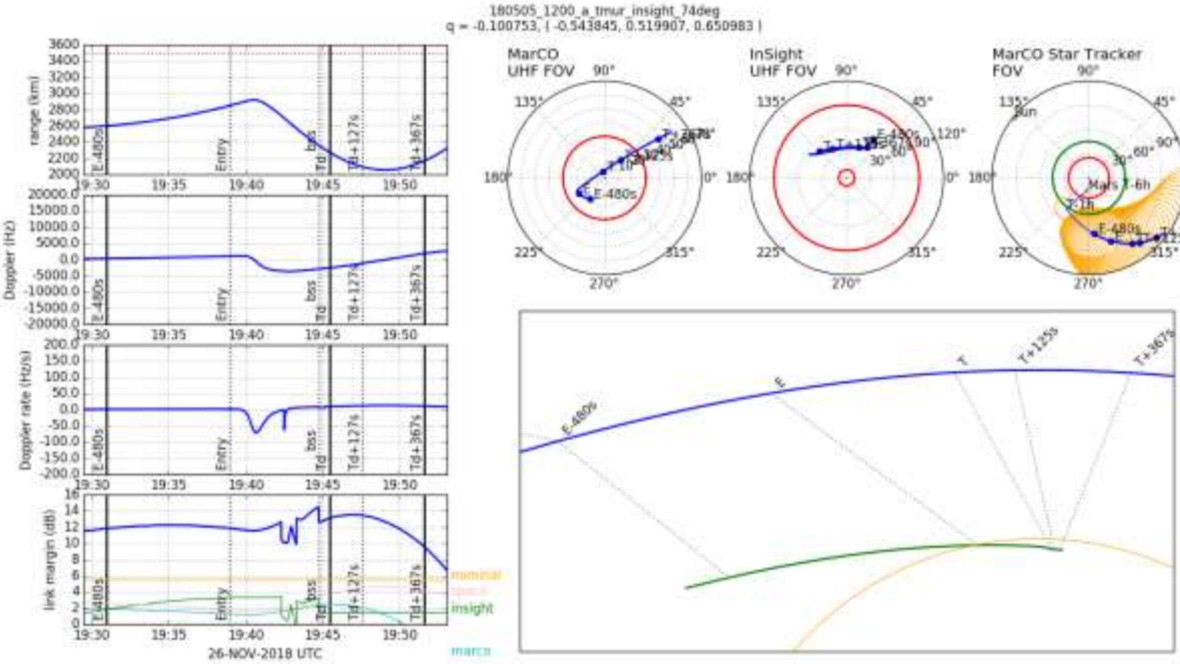

Fig. 2: Sample Relay Performance Analysis Results

During flight the relay performance analysis was refined in two ways: the period of interest was shrunk by six minutes at the start of the relay, since InSight was only transmitting a carrier but not telemetry during that period, and the margins were increased during the most challenging phase—parachute and divert—and decreased during the most predictable phase, while on the surface. Monte Carlo analyses were also performed using dispersed trajectories and attitudes for InSight as it descended into Mars, in order to evaluate the fitness of the targets against these perturbations [10]. Small adjustments were made to the targets in order to account for these effects.

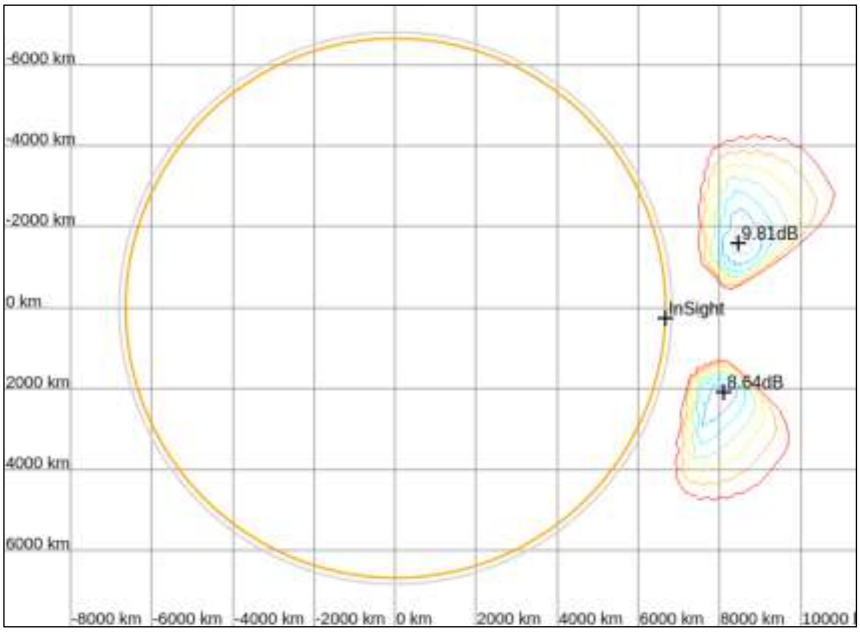

Fig. 3: 8 kbps UHF Relay Margin Contours at the Encounter B-plane

Trajectory Control

The launch vehicle and the separation mechanisms put the MarCO probes into trajectories that would have missed their Mars flyby targets by tens to hundreds of thousands of kilometers. The InSight trajectory to Mars needed to be biased away from the planet in order to comply with planetary protection requirements for the InSight spacecraft and for the upper stage. The resulting injection had dispersions that also had to be corrected, and the dispensers that ejected the MarCOs imparted an impulse to the probes that also moved them with respect to Mars. Up to five trajectory correction maneuvers were planned for each probe in order to remove injection bias and errors, trajectory perturbations and prediction uncertainty, and to aim to the flyby targets. As the propulsion system was new and had not been extensively tested before launch, the accuracy of maneuver execution was highly uncertain. A thruster calibration activity was planned to take place a few days after launch, in order to better characterize the propulsion system. Table 2 lists the trajectory correction maneuver schedule as it was planned before launch and as it was executed in flight.

Table 2: Trajectory Correction Schedule

Activity	**MarCO-A**		**MarCO-B**	
	Planned	**Actual**	**Planned**	**Actual**
TCM calibrations	May 8	May 8-13 Aug. 15-Sep. 21	May 9	May 15-21
TCM-1	May 20	May 22-Jun. 2	May 22	May 31
TCM-2	Aug. 10	Jul. 30-Aug. 13	Aug. 13	Aug 15-17
TCM-3	Oct. 24	Sep. 26-Oct. 3	Oct. 26	Sep. 25-Oct. 30
TCM-4	Nov. 15	*Not needed*	Nov. 16	Nov. 16
TCM-5	Nov. 23	*Not needed*	Nov. 24	*Not needed*

Navigation Results

Launch and First Station Acquisition

InSight was accurately launched by an Atlas V-401 from Vandenberg Air Force Base, California, on May 5, 2018, 11:05 UTC. The MarCO CubeSats separated nominally from the upper stage, deployed their solar panels, and turned on their attitude control system to achieve the pre-programed initial attitude. Soon after, each probe emitted a short telemetry burst that was received by the DSN antennas, confirming a successful deployment after spending months turned off while stowed in their dispensers. Processing of the post-launch InSight trajectory and the first day of 2-way data recorded for MarCO resulted in the prediction shown in Fig. 4. If left uncorrected, MarCO-A would had passed Mars 153,000 km away from its surface, and MarCO-B, 87,000 km.

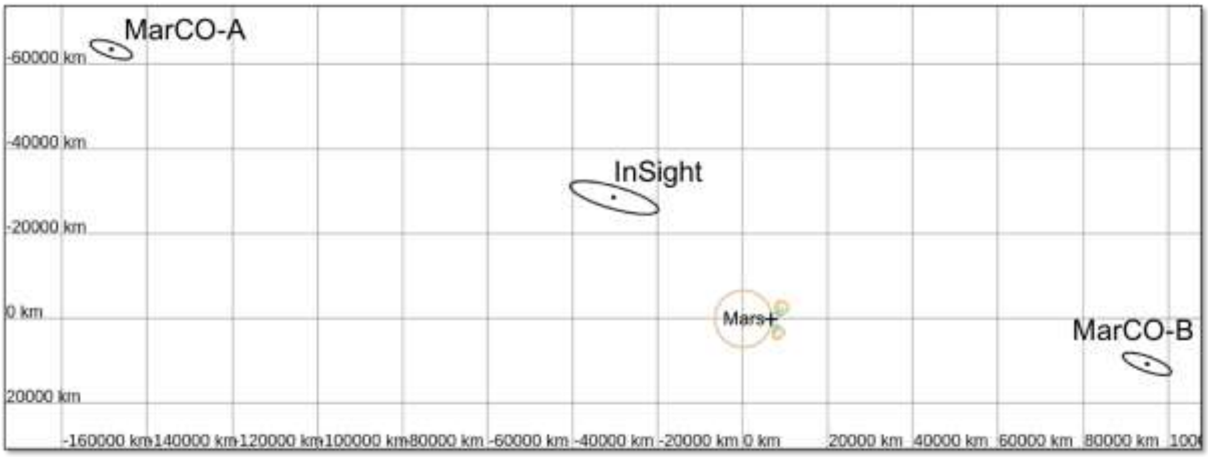

Fig. 4: Predicted 3-σ Trajectory Uncertainty Mapped to the Mars B-plane After Launch

Cruise

The first tracking passes confirmed that the Iris radio was working properly and produced good quality Doppler and range data. Trajectory predictions were provided to the DSN for antenna pointing that tracked a synthetic probe located between the two MarCOs, so the same set of predictions could be used to track either of the probes, since once the antenna was pointed at the midpoint both probes were within the half-power beam width of the antenna. The same applied to when the antenna pointed to InSight: after launch and before InSight executed its first trajectory correction maneuver, an antenna pointed to InSight would have both MarCOs within its half-power beam width. This allowed the DSN to monitor the MarCOs during InSight passes and to obtain telemetry from any of the three spacecraft as long as an antenna was pointed to either the MarCO midpoint or to Insight.

The day after launch, MarCO-B performed its first angular momentum reduction burn that resulted in an unexpectedly high translational component. It seems that the plenum valve, as discovered before launch, leaked and allowed liquid to condensate in the plenum, being expelled when the thrusters valves were actuated and producing a thrust level much higher than that created by a gaseous propellant. Over the following days, MarCO-A performed three short TCM calibration burns to characterize its propulsion system performance and thruster vector pointing. Blowdown thrustings were performed on B to characterize the plenum valve leak rate. Following that, a leak on a thruster valve also developed for MarCO-B that caused the angular momentum to build up, triggering multiple autonomous angular momentum reduction maneuvers, at a rate of about twice per hour. To mitigate the problem, the team developed a method to regularly empty the plenum by opening the four TCM thrusters simultaneously, to reduce the plenum pressure without significantly increasing the angular momentum. The maneuvers and the blowdowns significantly perturbed the MarCO-B trajectory, making orbit determination difficult: the spacecraft had multiple impulsive events per day, and only five two-hour tracking passes per week, resulting in many more unknowns than observables in the orbit determination filter. In order to add observables, data was obtained from the spacecraft telemetry in order to provide better initial estimates of the impulsive events. Event times, plenum pressure and temperature before and after the events, and attitude data were combined with tracking data to produce better trajectory estimates [9]. The plenum valve leak and the thruster valve leak on MarCO-B have persisted up to the current day, though the level of the plenum valve leak has changed unpredictably to higher or lower levels when the valve was actuated during angular momentum or trajectory maneuvers. Even with these mitigations in place, the MarCO-B trajectory was perturbed in two ways. First, the continuous leak, at a low level due to the regular blowdowns, still produced a torque and an acceleration; the spacecraft was commanded to rotate with the solar panels pointed to the Sun between tracking passes to reduce the torque and acceleration accumulation, but a component along the Sun line was still present. Second, the regular blowdowns produced impulses along the direction of the blowdown; that direction could also be chosen to either to minimize the effect on the trajectory or to alternate between directions in order to cancel it. The MarCO-B trajectory prediction had to account for these effects in order to be able to target it to its flyby aimpoint. A further mitigation measure that was implemented on both probes was to use extended dwells at particular attitudes designed to use solar radiation torque to reduce the total angular momentum and so avoid the reaction control wheels reaching high speeds that would trigger autonomous execution of angular momentum reduction burns. These burns were to be avoided, since every time that a burn was executed, the plenum valve would be actuated and it could transition from a desirable low-rate leak to an undesirable high-rate leak.

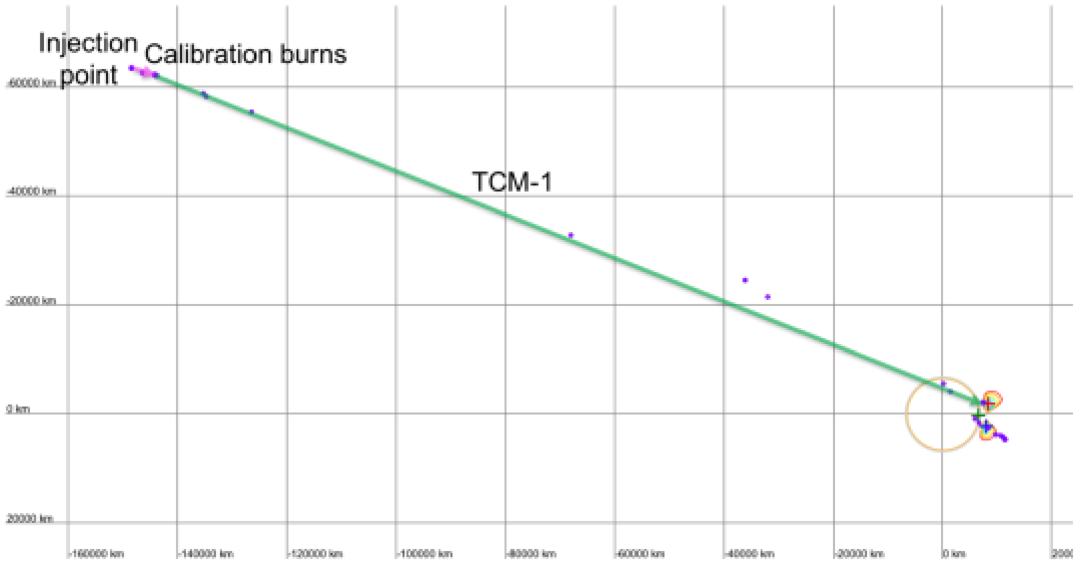

Fig. 5: MarCO-A TCM-1

After the mitigation measures were in place and after a better estimate of the effect of the leak events on the trajectory could be estimated, a test TCM was performed for MarCO-B on May 21. On May 22, a test segment for A’s TCM-1 was executed successfully, and it was followed by additional segments between May 24 and June 2, as show in Fig. 5. During these burns it was discovered that the reaction control system did not performed reliably for burn segment durations of more than 75 seconds, since pointing excursions could exceed a pre-established threshold and trigger an error that interrupted the segment. From then on, TCMs were split into multiple burn segments of 75 seconds or less in duration. Further TCM-1 segments for MarCO-B, using the same burn duration limitation, were executed on May 31, and after this the probe went back to a high-leak-rate state that significantly perturbed its trajectory again. Fig, 6 shows the MarCO-B path in the B-plane from injection to the execution of TCM-2. The first ΔDOR for MarCO-B was performed on June 15, and the first for MarCO-A on June 23. The quality of the MarCO ΔDOR measurements was comparable to that for InSight, and it was soon realized that the signal levels for MarCO were actually higher than for InSight, as the MarCOs used the reflectarray high-gain antenna, while the InSight cruise stage was only equipped with low and medium gain antennas.

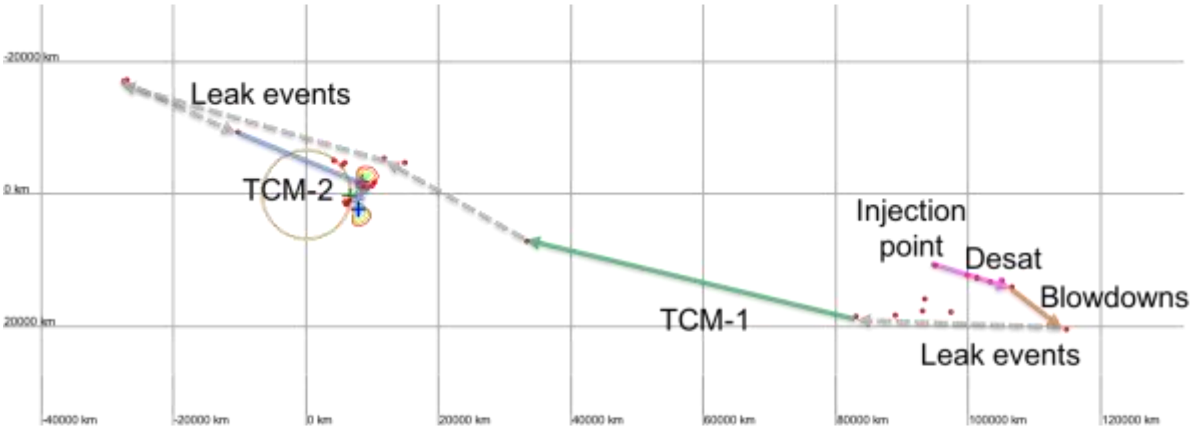

Fig. 6: MarCO-B TCM-1 and TCM-2

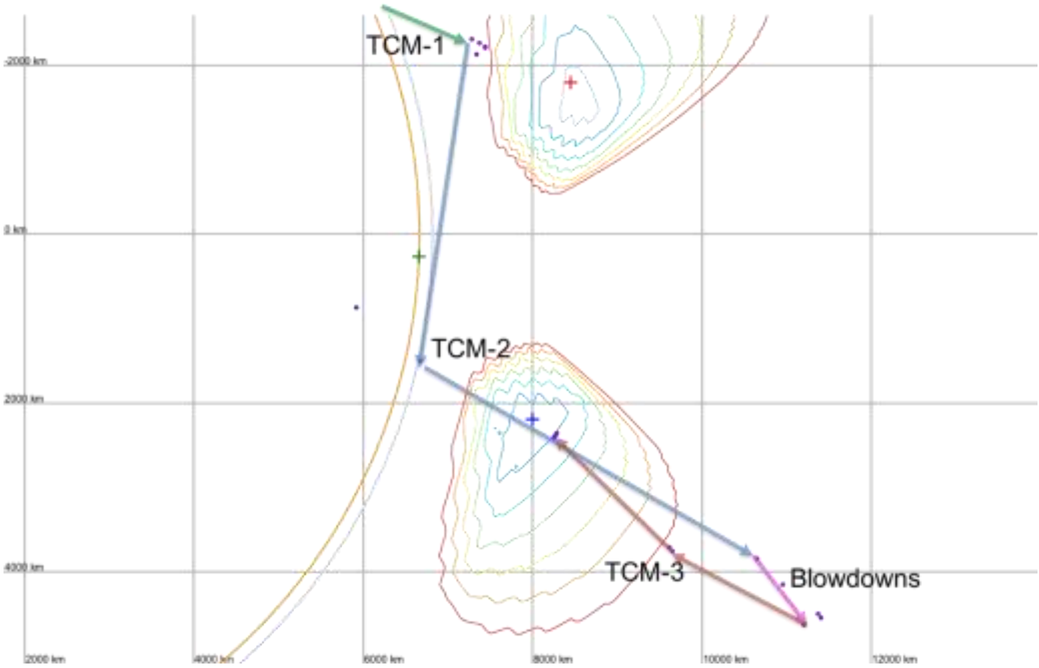

Fig. 7: MarCO-A TCM-2 and TCM-3

A first set of two TCM-2 segments were executed for MarCO-A on July 30, and a cleanup on August 13, but by that time an internal leak at the plenum valve had also developed for this probe, resulting on an expectedly large thrust level and execution error that made the probe overshoot the target, probably due to liquid having condensated in the plenum and being expelled when the thruster valves were opened (Fig. 7.) TCM-2 was also executed as a series of segments for MarCO-B, on August 15 and 17, resulting again on a high-level external leak state that moved the probe away from the target (Fig. 8.) A series of blowdowns were executed on MarCO-A between August 15 and September 21 to try to characterize the internal leak issue for this probe. TCM-3 was executed for MarCO-B between September 25 and October 30, with another high-leak-rate event developing between these two dates. For MarcO-A, TCM-3 was executed on September 26 and October 3.

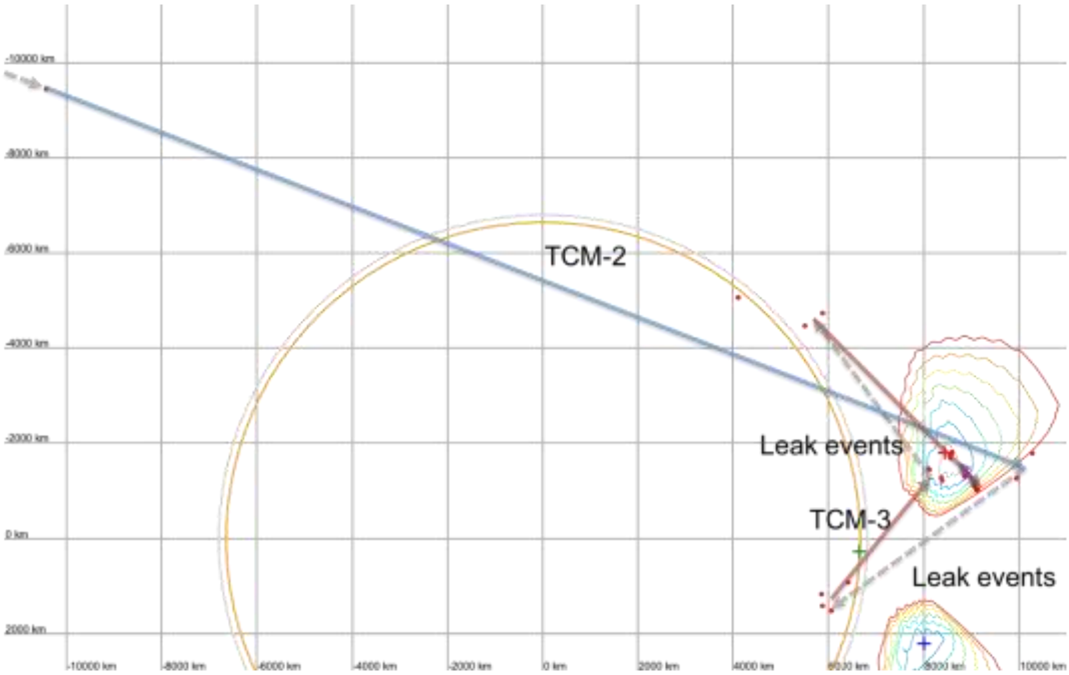

Fig. 8: MarCO-B TCM-2 and TCM-3

Approach and Flyby

TCM-3 had left MarCO-A about 320 km and 58 seconds away from the southern target, and MarCO-B about 1000 km and 57 seconds away from the northern target. Monte Carlo analysis was performed to evaluate the need of further trajectory correction maneuvers for both probes (Fig. 9.) The analysis showed that MarCO-A's performance was already acceptable and there was not much to gain from performing an additional TCM, while for MarCO-B the link margin was negative for a significant percentage of the cases analyzed. The decision was made to execute one more TCM for MarCO-B, but also to have the probe perform blowdowns after the maneuver with the Earth on the +X side of the probe so any high-leak-rate effects would move the trajectory in the least-damaging direction in the B-plane, roughly away from InSight, where the loss of link margin was less pronounced. The optimal TCM design called for a total burn time of 162 seconds, but only two 75-second segments were commanded to comply with burn duration limitations and to avoid a possible overburn. The maneuver was executed successfully on November 16, ten days before the flyby, and afterwards the plenum valve leak, while increasing slightly, was small compared with previous events. MarCO-B ended up flying about 110 km and 5 seconds away from the optimal target.

During the final approach and in preparation for the flyby the number of ΔDORs performed on the MarCOs increased to about four per week, greatly improving the trajectory prediction accuracy. Trajectory estimation and Monte Carlo link budget analysis for both probes showed that performing an additional trajectory correction was not warranted. Orbit determination solutions were consistent and stable on the days before the flyby, with MarCO-B drifting upwards in last ten days by tens of kilometers due to the blowdown impulses.

The Mars flyby took place on November 26, 2018, while InSight descended to Mars. Both MarCOs were successful in relaying the InSight data, with only small data losses during plasma blackout and when the InSight radio switched modes. Among the data relayed was the first picture taken by InSight on the surface of Mars. Had the MarCOs not relayed the data in near real-time, it would have taken hours for the same data to be transmitted by MRO and decoded on the ground. MarCO-A's closest approach to Mars happened at 19:44:11 UTC, at a distance of 1627 km to the surface of Mars, and at 19:46:35 UTC for MarCO-B, at a distance of 1750 km. Orbit determination performed with data in the close proximity of Mars showed that the range delays for the probes were off by about 6120 nsec for MarCO-A and by 4525 nsec for MarCO-B. Since the error in range of the Earth-Mars ephemerides was assessed to be about 40 m at this time, it seems that most of this offset may be due to the testing setup or to firmware changes in the radio after the ground DSN compatibility testing was performed. This discrepancy did not have any significant effect on the flyby performance, as an error of this magnitude only changed the flyby aimpoint by one kilometer, and the time of closest approach by less than one second.

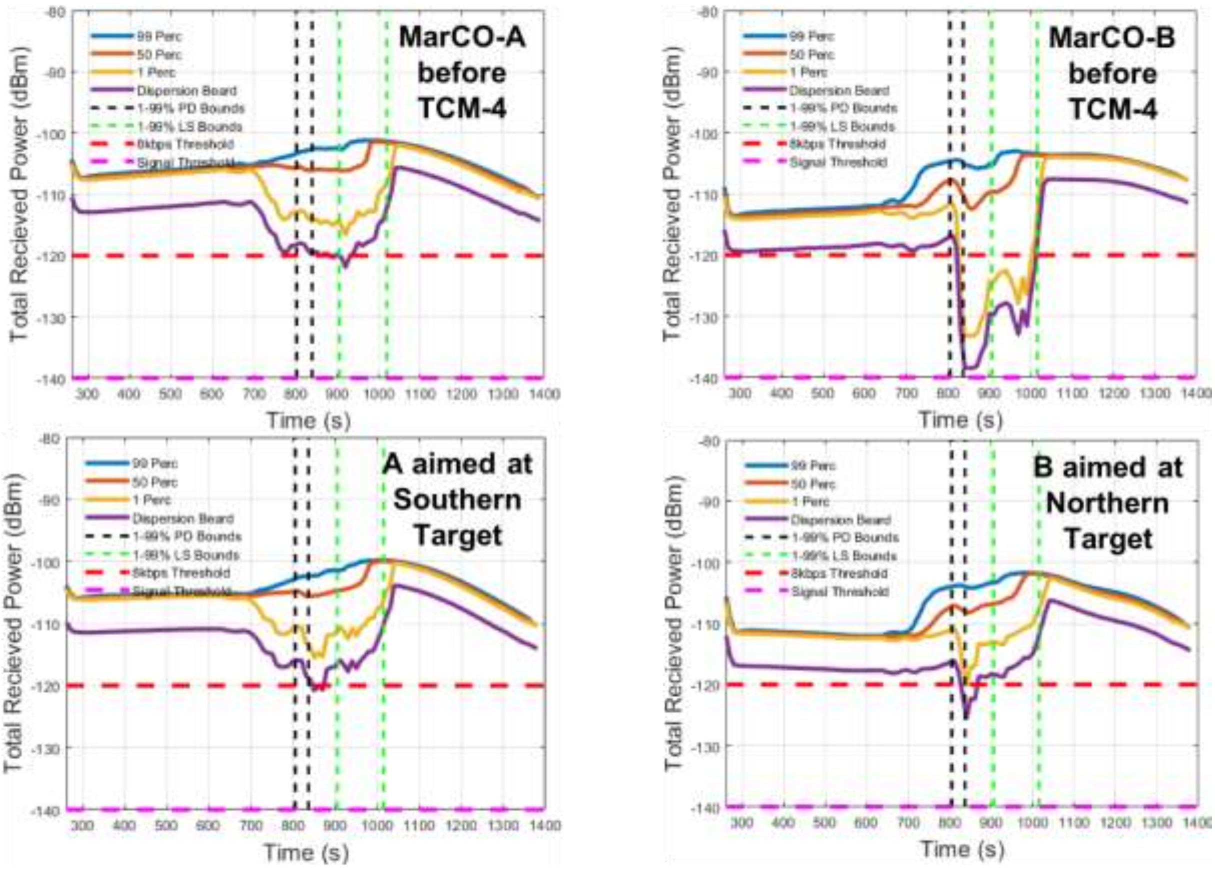

Fig. 9: Monte Carlo Evaluation for the TCM-4 Decision.
UHF link margin vs. time starting at ten minutes before InSight's entry.
Analysis and plots provided by Daniel Litton, LaRC [10]

Conclusion

The two MarCO probes were the first CubeSats ever to be operated in deep space, and the smallest spacecraft ever to be independently navigated to another planet. Despite some difficulties due to the use of new subsystems and components, the MarCO team was successful in delivering the probes to their flyby of Mars using their ingenuity to overcame severe operational limitations, when compared with larger spacecraft, and even a continuing propellant leak. The Iris radio, despite its larger than usual Doppler and range biases, performed very well, producing high-quality Doppler, range, and ΔDOR. The communication antennas, especially the reflectarray, allowed these very small spacecraft to transmit data to the Earth at higher data rates than those used by InSight during cruise. The quality of the tracking data, of the relay margin analysis, and of the trajectory prediction allowed for the cancelation of the last two TCMs for A and the last TCM for B and significantly contributed to both probes performing successfully during the InSight EDL relay, delivering detailed telemetry data to the InSight mission control team and the first image taken by InSight after landing. The MarCO project has demonstrated that is possible to fly CubeSats in deep space, opening a new range of small mission concepts to solar system destinations.

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